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Polarization Resolved Near-IR Imaging of Sound and Carious Dental Enamel

Cynthia L. Darling¹, Kenneth H. Chan, and Daniel Fried

University of California, San Francisco, CA 94143-0758

Abstract

A thorough understanding of how polarized near-IR light is reflected from and transmitted through sound and carious dental hard tissues is important for the development of optical imaging devices. New optical imaging tools employing non-ionizing radiation are needed for the detection and assessment of dental caries. In this investigation, an automated system was developed to collect images for the full 16-element Mueller Matrix. The polarized light was controlled by linear polarizers and liquid crystal retarders and the 36 images were acquired as the polarized near-IR light is reflected from the occlusal surface or transmitted through thin sections of extracted human whole teeth. Previous near-IR imaging studies suggest that polarization imaging can be exploited to obtain higher contrast images of early dental caries due to the rapid depolarization of incident polarized light by the highly scattering areas of decay. In this study, the reflectance from tooth occlusal surfaces with demineralization and transmitted light through tooth thin sections with caries lesions were investigated. Major differences in the Mueller matrix elements were observed in both sound and demineralized enamel. This study suggests that polarization resolved optical imaging could be exploited to obtain higher contrast images of dental decay.

Keywords

Mueller Matrix; polarization; Imaging; Near-IR; reflectance; transillumination; dental hard tissue

1. INTRODUCTION

A thorough understanding of how polarized near-IR light propagates through sound and carious dental hard tissues is important for the development of dental optical imaging systems. New optical imaging tools for the detection and assessment of dental caries (dental decay) such as near-IR imaging and optical coherence tomography can exploit the enhanced contrast provided by polarization sensitivity. Stokes polarimetry was used in a previous study to monitor the state of polarization of incident linearly and circularly polarized light as it propagates through extracted human thin tooth sections¹. These measurements on extracted whole teeth and thin tooth sections at 1310-nm suggest that the degree of polarization is maintained through sound tooth enamel and transparent dentin and that different types of polarized light are depolarized at different rates. Polarized light is rapidly

depolarized by demineralized enamel and sound and demineralized dentin¹. The rapid depolarization of polarized light by dental caries in the near-IR provides high contrast for caries imaging and detection. Research with polarized scattered light deals with the entire scattering process in the context of Stokes and Jones vectors, Mueller matrices, and degree of polarization²⁻⁶. Polarized light can be completely described by six polarization states of light, four linear, and two circular used to construct the Mueller matrix-Stokes vector formalism⁷⁻¹⁰. There are many well-known examples of polarized and unpolarized light. The output light from a laser beam is typically highly polarized while familiar examples of unpolarized light would include a light bulb, or light from the sun. Unpolarized light is a random mixture of all possible polarization states. The ability of polarized light to aid imaging of skin pathology is extensive¹¹⁻¹². Certain elements of the Mueller-matrix have been found to yield significantly higher contrast of known cancerous lesions due to significant changes in light scattering and tissue birefringence¹³⁻¹⁴. Dental hard tissues are also highly birefringent and demineralization results in marked increases in light scattering and large changes in birefringence. Polarized light microscopy has been used extensively for more than a hundred years to study dental caries¹⁵ due to these changes and various methods have been developed using different inhibition fluids to quantify the severity in thin tooth sections. We have found that the highest transparency of dental hard tissues lies in the near-IR region near 1310-nm¹⁶⁻²¹. Therefore we believe that the near-IR is best suited to provide high contrast imaging of dental caries. Polarization resolved imaging could remove most of the glare from the surface and enhance the contrast of the underlying tissue. In this investigation, we were able to show that there are major differences between the diagonal and off-diagonal elements of the normalized Mueller-matrix in both the reflectance images from the tooth occlusal surfaces and in the transmitted light through tooth thin sections.

2. MATERIALS AND METHODS

2.1 Sample Preparation

Extracted molars from patients in the San Francisco Bay area were collected with approval from the UCSF Committee on Human Research, cleaned and sterilized with gamma radiation. Whole teeth were inspected for lesions using near-IR transillumination and then stored in a 0.1% thymol solution. Whole carious teeth were imaged in reflectance mode. Additional teeth with lesions were sectioned and one slice from each tooth was selected for transillumination imaging after the surface was polished with aluminum oxide down to a finish of 0.3 microns. The tooth sections were 200-300- μ m thick to facilitate comparison with microradiography and polarized light microscopy.

2.2 Imaging Setup

A NoblePeak Vision Triwave Imager, Model EC701 (Wakefield, MA) was used that employs a Germanium enhanced complementary metal oxide semiconductor (CMOS) focal plane array sensitive from 400-1600-nm with a larger array (640 $\times$ 480) and smaller pixel pitch (10- μ m pixels) as shown in the experimental setup of Fig 2. A three component, modular 7X NIR precision zoom lens consisting of a focusable lower module, a manual upper zoom module and a 1.5 TV tube from Edmund Scientific (Barrington, NJ) was used with the CMOS focal plane array (FPA). The field of view was adjustable from 0.81 to 5.6-

mm, the magnification from 1.7X to 11.8X, and the Numerical aperture from 0.036 to 0.12. Long-pass (LP) filters at 1300 and 1400-nm were used to filter the NIR light. Unpolarized light was supplied from a tungsten-halogen 150-W fiber-optic illuminator, FOI-1 E Licht Company (Denver, CO) coupled to an adjustable aperture. The incident polarization states were controlled electro-optically via a rotating linear polarizer and a liquid-crystal voltage-dependent variable retarders with attached compensator Meadowlark Optics (Frederick, CO) with the ability to alter the incident polarization state between H (linear horizontal), V (linear vertical), P (linear +45), M (linear -45), L (left circular) and R (right circular). After passing through the sample, the polarization states of the emerging light were analyzed by an additional electro-optic variable retarder, and a near-IR linear polarizer. The 12-bit images were analyzed using image analysis software. The polarization states were confirmed using a PA530 polarimeter, ThorLabs (Newton, NJ).

3. THEORY

Using the Mueller-Stokes method²⁻⁶, the detected Stokes vector of an output beam of light after propagating through an input linear polarizer, two liquid crystal retarders and an analyzer polarizer can be determined. The Stokes vector $\mathbf{S}$ describes the near-IR light polarization as:

$$\mathbf{S} = \begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix} = \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix}$$

The Stokes vector $\mathbf{S}$ elements S_0 , S_1 , S_2 and S_3 are defined relative to the following intensity measurements: I is the total light intensity, Q is the intensity difference between horizontal and vertical linearly polarized light, U is the intensity difference between a linearly polarized +45 and a linearly polarized -45 light, and V is the intensity difference between left and right circular light. The Stokes vector formalism is written for $\mathbf{H} = (S_0 \ S_1 \ S_2 \ S_3) = (1100)$, $\mathbf{V} = (1-100)$, $\mathbf{P} = (1010)$, $\mathbf{M} = (10-10)$, $\mathbf{R} = (1001)$ and $\mathbf{L} = (100-1)$.

For Mueller-matrix imaging $\mathbf{S}_{\text{out}} = \mathbf{M}_{\text{sample}}\mathbf{S}_{\text{IN}}$, there are basically six polarization states of light, four linear (H, V, P, and M) and two circular (R and L), used to construct the Mueller-matrix. The sample Mueller matrix shown below relates the Stokes vector $\mathbf{S}_{\text{IN}}$ of the light impinging on a sample to the light leaving the sample $\mathbf{S}_{\text{out}}$ and is calculated by a combination of input and output polarization states. There are 36 equations with 36 unknowns and the Mueller matrix is over determined when all possible combinations of

$$\begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix}_{\text{OUT}} = \begin{bmatrix} M_{11} & M_{12} & M_{13} & M_{14} \\ M_{21} & M_{22} & M_{23} & M_{24} \\ M_{31} & M_{32} & M_{33} & M_{34} \\ M_{41} & M_{42} & M_{43} & M_{44} \end{bmatrix} \begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix}_{\text{IN}}$$

the six input and six output polarization states are used.

Sixteen elements of the Mueller-matrix are: $M_{11} = HH + HV + VH + VV$, $M_{21} = HH - HV + VH - VV$, $M_{31} = HP - HM + VP - VM$, $M_{41} = HR - HL + VR - VL$, $M_{12} = HH + HV - VH - VV$, $M_{22} = HH - HV - VH + VV$, $M_{32} = HP - HM - VP + VM$, $M_{42} = HR - HL - VR + VL$, $M_{13} = PH + PV - MH - MV$, $M_{23} = PH - PV - MH + MV$, $M_{33} = PP - PM - MP + MM$, $M_{43} = PR - PL - MR + ML$, $M_{14} = RH + RV - LH - LV$, $M_{24} = RH - RV - LH + LV$, $M_{34} = RP - RM - LP + LM$, $M_{44} = RR - RL - LR + LL$. The notation is as follows: the first term represents the input polarization state while the second term represents the output polarization state.

The acquired images were imported into an image analysis program to generate each element of the matrix. The M_{11} term is sometimes referred to as the transmission element and the other fifteen elements of the Mueller-matrix are normalized to M_{11} after subtracting off the dark current.

4. RESULTS & DISCUSSION

The initial aim of this investigation was to construct the sixteen elements of the Muller-matrix that will provide a complete description of the polarization properties of a tooth sample. Figure 3 shows a series of 36 unprocessed images taken with the setup of Fig. 1. This is a tooth section that is 300- μm thick with an occlusal lesion that penetrates through the enamel and into the underlying dentin. The image was taken with a 1300-nm LP filter. In the upper left hand corner are two letters that designate the initial and final polarization states selected and analyzed. Each image shows the same tooth slice in different polarization states. The enamel is still transparent in most of the images but varies in intensity from image to image because of the birefringence of the tissue. The dentin-enamel junction (DEJ) is very distinct showing a dark line separating the enamel from the dentin. The dentin just below the DEJ is very transparent. The dentin is very dark in the images because of the high scattering coefficient and it is very hard to discern any meaningful differences. The carious region is located in the pit of the fissure and extends down into the transparent dentin and is very dark. The edge of the tooth is dark due to the tooth curvature. From the 36 images in Fig. 3, the Mueller matrix elements of Fig. 4 can be constructed from equation 2 and normalized to the M_{11} element. The scale of the Mueller matrix elements ranges from -1 to 1 with 0 exhibiting no preferential polarization. The M_{11} image equals 1 when normalized and is not shown normalized in Fig. 4. In Fig. 4, the M_{12} , M_{13} , M_{14} , M_{21} , M_{31} , M_{41} element are close to zero for the enamel, dentin, and caries regions. The remaining nine elements show the greatest contrast. The intensity in the normal dentin was too low for reliable analysis.

It is clear from these initial images that there are major differences in the specific matrix elements for both sound and carious enamel.

Figure 5 shows four unprocessed NIR images representing the linear horizontal and vertical combinations (HH, VH, HV, VV) of the occlusal surface of a molar with extensive demineralization or hypomineralization (developmental defect). These reflectance images were taken using a 1400-nm LP filter. The longer NIR wavelengths where water absorption is higher is advantageous for increasing contrast in reflectance images see paper 7884-33 in

this proceedings and the hyperspectral NIR imaging paper by Zakian et al.²² The HV and VH cross polarization components have the highest contrast between the sound and demineralized enamel. However, the surface contour information is lost in the cross polarization images while the co-polarization images HH and VV show the best details of the surface. Normalized elements of the Mueller Matrix are shown for the same tooth in Fig. 6. The diagonal elements show the lesion with high contrast while maintaining resolution of the tooth surface detail.

It is clear from these initial images that there are major differences in the specific matrix elements for both sound and carious enamel. More extensive studies are planned involving both transmission and reflectance measurements. We anticipate that specific elements of the Mueller-matrix will yield the optimal contrast between sound and demineralized dental hard tissue.

5. ACKNOWLEDGMENTS

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Fig 1. Mueller Matrix transillumination imaging setup consisting of tungsten light source, optical density filter, aperture, linear polarizer, liquid crystal retarder, sample mount, liquid crystal retarder, linear polarizer, and Noble Peak imaging camera with near-IR filter.

Fig. 2.
Mueller Matrix reflectance imaging setup. A non-polarizing beamsplitter is added for reflectance measurements.

Fig 3.

Unprocessed intensity images of a tooth section (300 μm thick) used to construct the matrix elements of the Mueller Matrix. The notation is as follows: the first term represents the input polarization state while the second term represents the output polarization state for H, V, P, M, R and L.

Fig 4.
Normalized elements M_{ij}/M_{11} of the Mueller-matrix with M_{11} image shown without normalization.

Fig 5.

Unprocessed intensity NIR images reflected from the occlusal surfaces of an extracted human whole tooth used to contrast the matrix elements of the Mueller Matrix in Fig.6. Only the linear horizontal and vertical combinations (HH, VH, HV, VV) showed.

Fig 6.
Normalized elements M_{ij}/M_{11} of the Mueller Matrix for the reflectance imaging with M_{11} image shown without normalization.